

Establishing a Common Phase Reference for Comparing Synthetic Data to RF Range Measurements

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Abstract— Discrepancies can result when creating common data sets consisting of comparable synthetic and measured range complex scattered field samples when the phase references of each do not coincide. This can be especially true when using signal processing techniques to produce one dimensional (range profiles) or two dimensional (Synthetic Aperture Radar or SAR images) representations of the target scattered field where range bins and cross-range bins are formed. Range profiles and SAR images can be misaligned or have different bin amplitudes due to target scatterers in synthetic and measured scenarios shifted with respect to one another. Obtaining equivalent data samples requires attention to the measured data calibration process and phase reference location. This paper will address the common phase reference problem by an analysis of experimental data for specific targets and rotation system. Suggestions are provided for possible solutions to current challenges. The data analysis will include synthetic and measured range data comparisons, range calibration, and target position and range alignment processes using Theodolite laser measurements.

I. INTRODUCTION

In order to accurately compare synthetic and measured data, a common phase reference and target rotation scheme should be established so that both data sets are properly aligned. Manual alignment or automatic alignment algorithms can only align this data within one range bin or cross-range bin after signal processing, but may be off in alignment on a sub-bin level. The measured and synthetic target scatterers could still be shifted with respect to one another as much as one bin (or resolution cell). Therefore, the magnitude and phase at each bin of each data set could be different due to this misalignment.

Devoting proper attention to the measured target calibration process and the target rotation system as well as CAD model alignment relative to the origin in synthetic calculations, one can achieve equivalent geometry alignment in measured/synthetic data sets. This is especially true when using complex (coherent) data where the phase as well as the magnitude may be important.

II. APPROACH

Measured electromagnetic (EM) fields and laser position data will be compared to synthetic results (an asymptotic solution; the method of moments solution, which should be more accurate than the asymptotic solution, is currently being computed, but did not complete in time for this paper). Two targets were measured. The first was a sphere mounted on a hexagonal rod which was used to check spatial position and rotation calculations. The second was an aluminum plate with cans (three different sizes) mounted to it which was chosen for its scintillating EM properties in frequency and angle and will be referred to as the Test Target. The data was measured in the Air Force Research Laboratory Advanced Compact Range (ACR) facility. The target positioner and calibration process used in the ACR will be focused on in the following sections, but the problem of creating common data sets will apply to range measurements in general. Details of a particular range (calibration and rotation methods) will dictate its specific solution.

III. RANGE COORDINATE SYSTEM AND POSITIONER

A coordinate system was established in the compact range utilizing a Theodolite (Sokkia Total Station Set 230R). Reflective targets were placed on the front, back and side walls of the chamber and measured with the Theodolite and used as reference points. A 31" square flat plate was mounted on the pylon rotator and "peaked" using the radar to establish a plate orientation that produced a peak in the RCS at a fixed frequency. Reflective targets were placed on the plate and pylon and measured with the Theodolite. These points were used to calculate a normal vector on the plate in the main reflector direction which was assigned the range +x-direction (so the plane wave from the reflector is traveling in the $-\hat{x}$ direction). The range +y-direction is defined as the cross-product of the upward normal unit vector on top of the pylon rotator with the range +x direction unit vector. The range +z-direction is then the cross-product of the +x and +y range unit vectors.

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An illustration of the range coordinate system is shown in Fig 1.

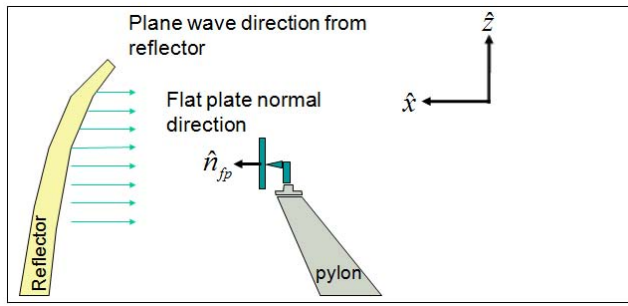


Figure 1. Range Coordinate System

In a test to confirm our understanding of the target positioner rotation and signature alignment with measured data, a 20.3 cm sphere was attached to a rod and mounted to the pylon positioner. The rod had a hexagonal cross-section and the distance from the center of the sphere to the center of the rotator was approximately 109 cm. Small reflective targets were placed on the sphere and rod which were used in conjunction with a Theodolite to measure the sphere location. These reflective targets show up as small white dots in the photograph of Fig 2. Theodolite points on the sphere surface were collected at $[0^\circ, 0^\circ]$, $[0^\circ, +20^\circ]$, and $[+45^\circ, +20^\circ]$ (i.e. [azimuth, elevation]). Sphere points at each of the three rotator positions were used to compute the center of the sphere. All positive rotations in this paper conform to the right hand rule convention and azimuth rotation is about the target z-axis and elevation rotation is about the rotator y-axis.



Figure 2. Sphere on Hex Rod Mounted to Pylon Rotator

The expected location of the sphere was computed by applying the appropriate coordinate transformation for each vector from the Theodolite coordinate system to the rotator coordinate system (the rotator coordinate system is defined as the target coordinate system at $[0^\circ, 0^\circ]$). A discussion on transformations can be found in [1].

A vector \bar{v}_{elr} from the elevation rotation axis to the rotator center as well as a vector \bar{v}_{rs} from the rotator center to the sphere center were computed at a rotator position of $[0^\circ, 0^\circ]$. These vectors were then transformed from the Theodolite coordinate system to the rotator coordinate system. The appropriate az/el transformations were performed and the

vectors were transformed back to the Theodolite coordinate system. A vector \bar{v}_{os} from the Theodolite coordinate system origin to the sphere center was computed as:

$$\bar{v}_{os} = \bar{v}_{oel} + \bar{v}_{elr} + \bar{v}_{rs} \quad (3)$$

The vector \bar{v}_{oel} is from the Theodolite coordinate system origin to the elevation axis of rotation. \bar{v}_{os} was computed for all three sphere positions mentioned earlier and compared to the Theodolite points. Obviously the distance from the computed sphere center at $[0^\circ, 0^\circ]$ was zero since this was the reference position assumed. The distance between the computed sphere position and the Theodolite measurement at $[0^\circ, +20^\circ]$ was 0.419 cm and 0.511 cm at $[+45^\circ, +20^\circ]$. These values seem fairly reasonable since there was likely some flexing of the rod. It also suggests that we have an accurate understanding of the positioner rotation.

IV. MAINTAINING A COMMON PHASE REFERENCE

Fig 3 shows a CAD model rendering of the Test Target and Fig 4 shows the physical Test Target mounted on the range pylon.

It is common, when generating synthetic data using CEM (computational electromagnetic) codes, to calculate scattering fields from a certain geometry which is oriented relative to some fixed coordinate system. All rotations, incident and observation directions are measured relative to the origin of that coordinate system. The zero phase reference for the incident field is also typically at the origin.

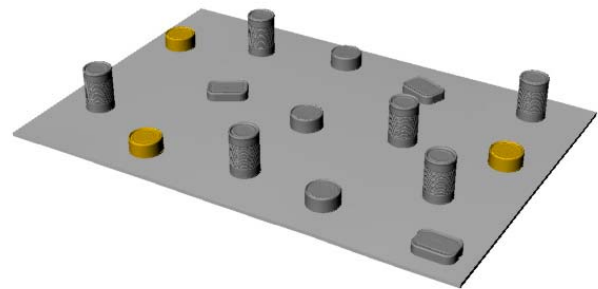


Figure 3. Test Target, Plate with Cans CAD Model

A typical model for a calibrated electric field (E field) from a measurement range is [2] [3]:

$$E_m = \frac{E_t - E_{bt}}{E_c - E_{bc}} E_p \quad (4)$$

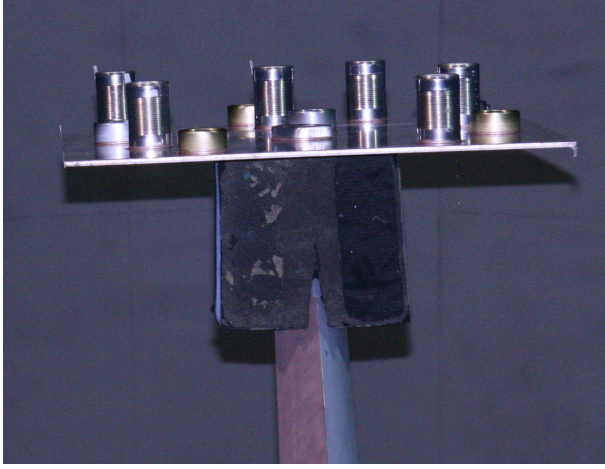


Figure 4. Test Target on Pylon Rotator, Rear View

Where:

E_m is the target calibrated E-field,

E_t

E_{bt} is the measured target background E-field,

E_c is the measured calibration target E-field including background,

E_{bc} is the measured calibration target background E-field, and

E_p is the predicted calibration target E-field.

So it is evident from (4) that the phases of the measured calibration target and the predicted calibration target E-fields dictate the phase center for the target calibrated E-field. Therefore, it is important to center the calibration target on the azimuth rotator (at 0° elevation) to best match synthetic data sets where the phase center and point of rotation is at the origin.

One difference between synthetic data calculations and an RF measurement system can be the method of target rotation. The measurement system azimuth rotation axis is not always coincident with the elevation rotation axis as it typically is in synthetic data calculations. This was the case for the pylon “kneeling rotator” shown in Fig 5 which was used for our measurements. A target can be mounted on top of the tall cylindrical structure. The calibration target was centered on the azimuth rotation axis at a 0° elevation position. So the measurement zero phase reference is indicated by the vertical line which passes through P_o and is also the azimuth rotation axis at 0° elevation. As the positioner kneels forward or up in elevation, it can be seen that P_o has moved with the rotation mechanism to $P_{o'}$ and is now a distance d_θ up range relative to the 0° elevation position as shown in Fig 5. An undesirable result of this is that the target position relative to the phase reference along the vertical line through P_o changes as a

function of the elevation angle instead of remaining constant as is typical in synthetic computations.

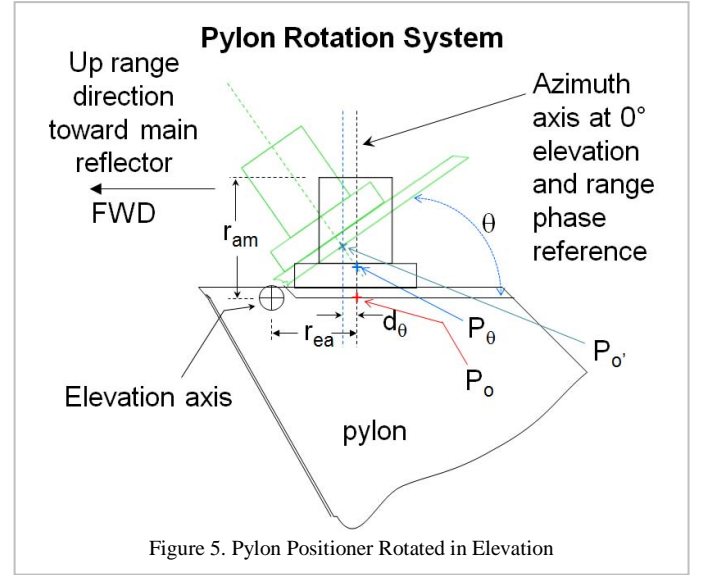


Figure 5. Pylon Positioner Rotated in Elevation

One solution to ensure the phase is equivalent for the synthetic and measured data is to phase shift the measured data by $e^{-j\gamma}$, assuming $e^{+j\omega t}$ convention, for each elevation where γ is defined as:

$$\gamma = 4\pi d_\theta / \lambda = 4\pi f d_\theta / c \quad (5)$$

$$d_\theta = r_{ea} (1 - \cos \theta) \quad (6)$$

Where f is the frequency, c is the speed of light, and λ is the wavelength.

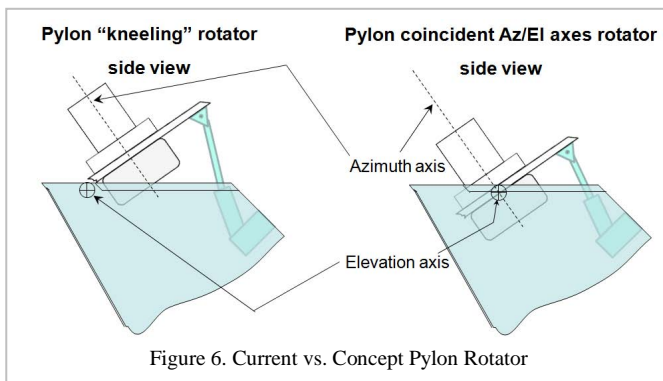
Another possibility would be to shift the CAD model origin below $P_{o'}$ along the azimuth rotation axis to P_θ so that the phase reference of the synthetic and measured data would be equivalent. This distance is:

$$\overline{P_o P_\theta} = d_\theta / \sin \theta = r_{ea} [\sin \theta / (1 + \cos \theta)] \quad (7)$$

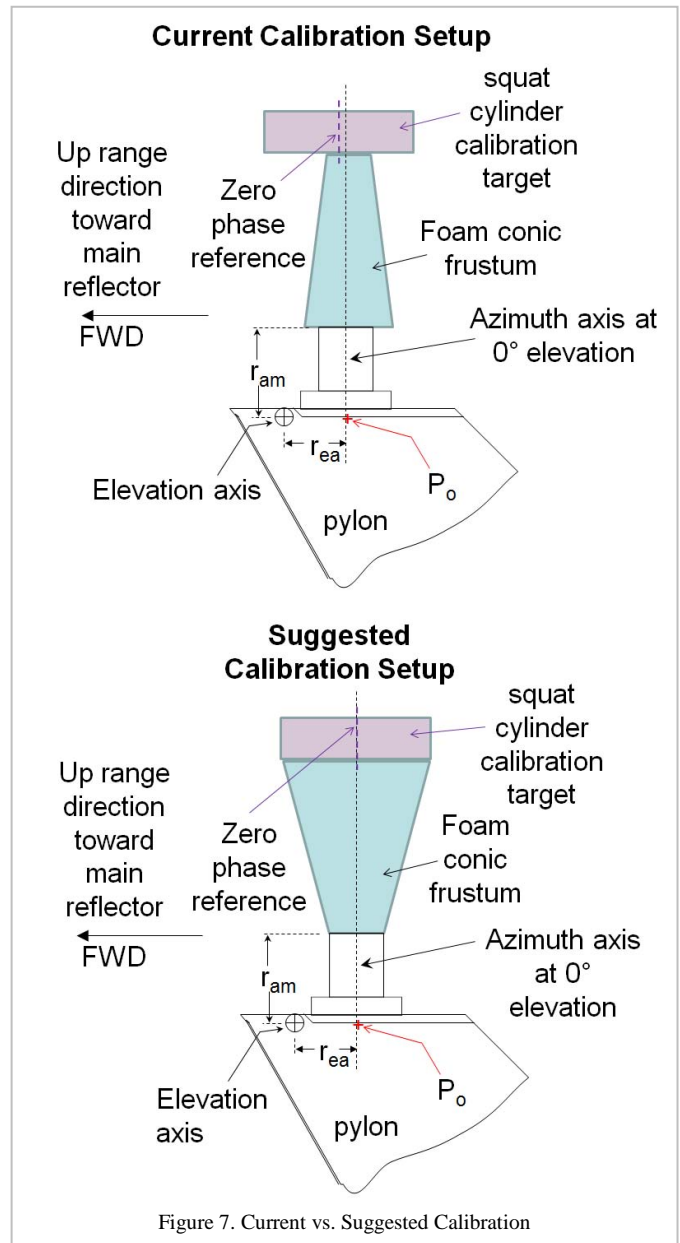
There are at least two possible problems with this solution. One is that this would require a separate CAD model for each elevation which could be very computationally expensive for some CEM codes. Another problem is that the elevation rotation point relative to the phase reference changes as a function of elevation angle. This is undesirable since this distance is not constant as it is in azimuth rotation. As an example, when looking at 1-D range profiles, the target origin (which is on the azimuth rotation axis) moves up range relative to the phase center as the elevation angle increases (see the red plus sign for 0° elevation and the green one for an

elevation angle of θ in Fig 5). Ideally, one would like the target phase reference to be at the intersection of the azimuth and elevation rotation axes.

A third solution would involve re-designing the pylon rotator such that the azimuth and elevation rotation axes intersect. Fig 6 shows the current pylon rotator for our measurements at the left and a suggested re-designed rotator at the right of the figure where the azimuth and elevation axes intersect. Although it might appear to be a simple change on paper, the authors realize that this modification could significantly reduce maximum weight capacity and require other rotation system changes as compared to the same sized “kneeling” rotator. It would, however, allow at least smaller targets to have a single point of rotation for azimuth and elevation angles on a reduced cross-section pylon.



The calibration measurement can be another source of phase difference between synthetic and measured data. Alignment of the calibration target with the azimuth rotation axis is required. Fig 7 illustrates the current calibration target setup for our tests at the top and a suggested setup at the bottom. The current setup utilizes a foam cone frustum to support the squat cylinder which is larger than the rotator at the bottom and smaller than the squat cylinder at the top. Centering the foam conic frustum on the rotator is followed by balancing the squat cylinder on top. This approach can lead to slight alignment errors. Theodolite measurements of the azimuth rotator and squat cylinder revealed that the squat cylinder was aligned nearly perfectly in the down range direction, but was off by 1.0 cm in the cross-range direction relative to the azimuth rotation axis. Although the down range direction is the important alignment measurement, the cross-range alignment error suggests that a range alignment error is possible with this setup. By machining or turning a foam column (so that it becomes a right cone frustum) to fit the rotator at the bottom and the squat cylinder at the top, the possibility for alignment error is reduced as shown at the bottom of Fig 7. A photo of the current calibration measurement setup is shown in Fig 8.



V. SYNTHETIC VS. MEASUREMENT RESULTS

Table 1 describes the experiment matrix being run with the experiments completed in time for this paper shown in light blue. Headings along the top of the table are “Chamber” for ACR chamber measurements, “Asymptotic” for asymptotic EM code results, and “Method of Moments” for method of moments EM code results. “E” refers to equivalence to the ACR target position (e.g. the synthetic CAD model is positioned equivalent to the ACR target position). The symbol “e” indicates equivalence to the synthetic CAD model position. “U” refers to the CAD model being in a different position relative to the ACR target position. “E” indicates a phase shift was applied to the data for equivalence to the ACR target position and “e” to a phase shift applied to the data for equivalence to the synthetic CAD model position. Experiment 1 shows results when all three data sets have the same phase reference as in the measured data for an elevation angle of 20°. Experiment 2 illustrates differences in the synthetic data as compared to the ACR chamber results due to CAD model position differences relative to the ACR target position. The third experiment is meant to show how the synthetic data can be phase shifted to compensate for difference in CAD model and ACR target positions. Experiment 4 is similar to Experiment 3, but the measured data is phase shifted to compensate for the difference in CAD model and ACR target positions. The last case is preferred since the synthetic data is computed with the CAD model in a static position relative to the origin. Benefits of this include less complexity and computation time for some EM codes since the CAD model is not required to move and the azimuth and elevation angles are all relative to the same origin (constant phase center with respect to rotation).

Table 1. Experiment Matrix

Experiment	Chamber	Asymptotic	Method of Moments
1	E	E	E
2	E	U	U
3	E	<u>E</u>	<u>E</u>
4	<u>e</u>	e	e

Completed Not Completed

Fig 9 shows a synthetic SAR image at 7.5 cm resolution for $[+25^\circ, +20^\circ]$ (VV polarization) where the CAD model was positioned to match the ACR target measurement at 20° elevation to obtain an equivalent phase reference (Experiment 1). A similar synthetic SAR image is shown in Fig 10 where the CAD model was positioned to match the ACR target measurement at 0° elevation even though the image was computed at 20° elevation (Experiment 2). The CAD model in Fig 9 was positioned 2.18 cm higher vertically (z-direction) than that of Fig 10. Notice that several pixels in the image of Fig 10 changed as compared to Fig 9 due to the slight difference in CAD model position. A third synthetic SAR image is shown in Fig 11 in which the same synthetic data was used as in Fig 10 with the exception that it was phase compensated according to (5), (6), and (7) for a 20° elevation measurement (Experiment 3). The images in Fig 9

and Fig 11 are identical indicating that phase shifting the data to compensate for differences in CAD model position and ACR target position is a reasonable approach to achieve a common phase reference. Fig 12 is an ISAR image generated from the ACR measured data for the same angles and polarization as in Figs 9 through 11. The images in Fig 9 and Fig 12 appear to be perfectly aligned indicating that the CAD model used to generate the synthetic data was positioned correctly (at least within the 7.5 cm resolution of the image, although we know it is much closer than this from Theodolite measurements). There are differences in pixel intensity of the images which are likely due to the asymptotic nature of the synthetic EM code, but the image patterns are very similar. As the method of moments code results are completed, a more comprehensive analysis of the data comparisons will be made.

VI. SUMMARY/CONCLUSIONS

It has been shown that observable differences can occur between two synthetic data sets using the same CAD model when a common phase reference is not observed. The magnitude of the differences is dependent on the specific geometry and the resolution of the data sets being compared. Although differences exist between the synthetic and measured data shown here, we have demonstrated that a common phase reference can be important in achieving accurate comparisons between two data sets. After our method of moment code results are completed, we hope to show a closer comparison between synthetic and measured data as well as a more detailed analysis of the alignment experiments outlined in Table 1. Suggestions have also been presented to improve the calibration target measurement and a pylon rotator that would be more compatible with synthetic calculations and maintain a common rotation point relative to the phase reference for all rotation angles.

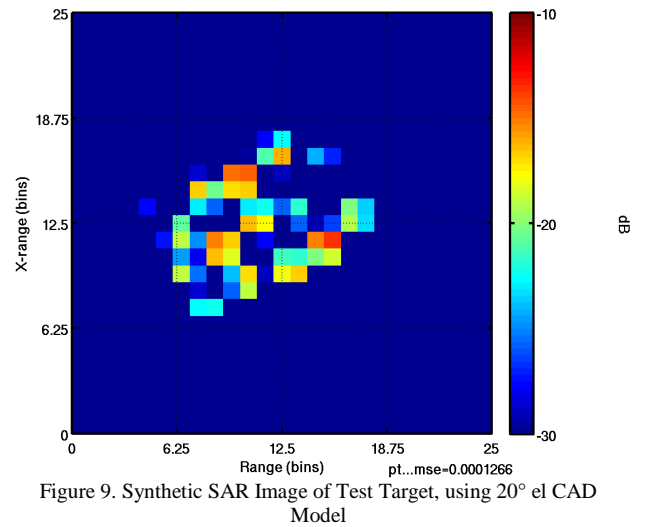


Figure 9. Synthetic SAR Image of Test Target, using 20° el CAD Model

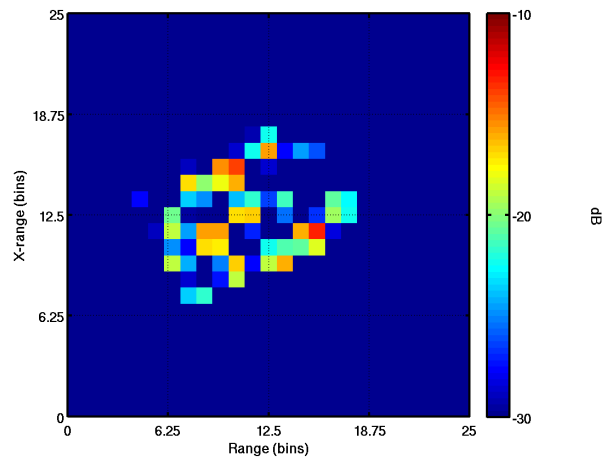


Figure 10. Synthetic SAR Image of Test Target, using 0° el CAD Model

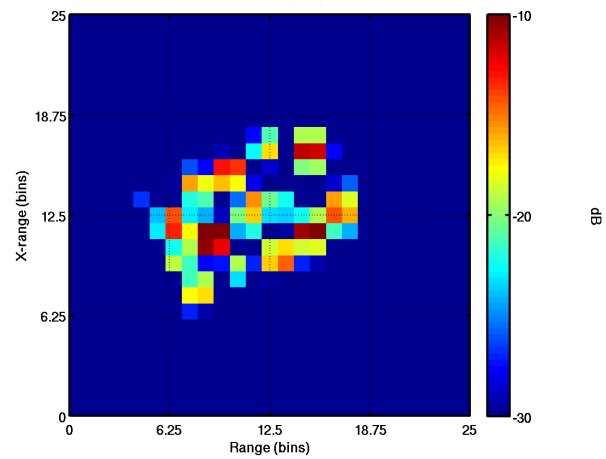


Figure 12. ACR ISAR Image of Test Target

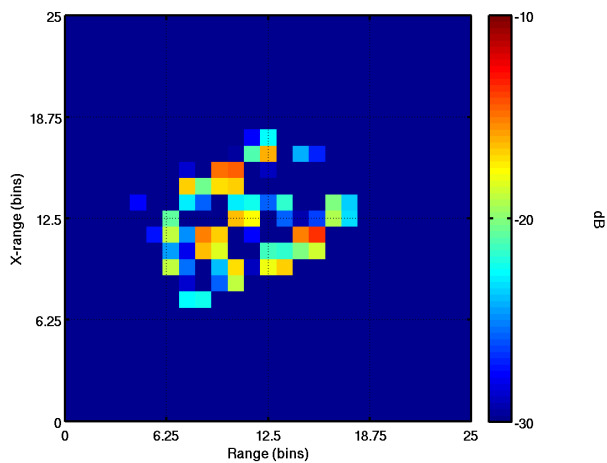


Figure 11. Synthetic SAR Image of Test Target, using 0° el CAD Model with Phase Compensation for 20° el ACR Measurement

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